

Observation of reentrant quantum Hall states in the lowest Landau level

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Measurements in very low disorder two-dimensional electrons confined to relatively wide GaAs quantum well samples with tunable density reveal reentrant $\nu = 1$ integer quantum Hall states in the lowest Landau level near filling factors $\nu = 4/5$ and $6/5$. These states are not seen at low densities and become more prominent with increasing density and in wider wells. Our data suggest a close competition between different types of Wigner crystal states near these fillings. We also observe an intriguing disappearance and reemergence of the $\nu = 4/5$ fractional quantum Hall effect with increasing density.

At low temperatures and subjected to a strong perpendicular magnetic (B), a low-disorder two-dimensional electron system (2DES) displays a myriad of novel collective states [1–3] arising from the dominance of the Coulomb interaction energy over the kinetic energy and the disorder potential. At high B , when the electrons occupy the lowest ($N = 0$) Landau level (LL) [4], the 2DES exhibits fractional quantum Hall effect (FQHE) at several series of odd-denominator LL fractional fillings $\nu = nh/eB$ (n is the 2DES density) as it condenses into incompressible liquid states [1–5]. At even higher B , the last series of FQHE liquid states is terminated by an insulating phase which is reentrant around a FQHE at $\nu = 1/5$ and extends to lower $\nu < 1/5$ [6–8]. This insulating phase is generally believed to be an electron Wigner crystal (WC), pinned by the small but ubiquitous disorder potential [6–8].

In the higher ($N > 0$) LLs, at the lowest temperatures and in the cleanest samples, other collective states compete with the FQHE states. These include anisotropic “stripe” phases at half-integer fillings for $N \geq 2$ and several insulating phases at non-integer fillings which exhibit reentrant integer quantum Hall effect (RIQHE) behavior [9–12]. The latter phases are most prominent in the second ($N = 1$) LL, and their hallmark feature is a Hall resistance (R_{xy}) which is quantized at the value of a nearby integer quantum Hall plateau and is often accompanied by a vanishing longitudinal resistance (R_{xx}) at the lowest achievable temperatures. The origin of these RIQHE phases is not entirely clear, although they are widely considered to signal the condensation of electrons in a partially-filled LL into “bubble” phases where several electrons are localized at one lattice site [9–13]. Such RIQHEs have not been seen until now in the $N = 0$ LL, consistent with the expected the instability of the bubble phases in 2DESs in the lowest LL [14].

We report here the observation of RIQHE in the lowest LL in very clean, high-density 2DESs confined to relatively wide GaAs quantum wells (QWs). Figure 1 highlights our main finding. It shows data taken in a 42-nm-wide GaAs QW at two different densities. At the lower density, the R_{xx} and R_{xy} traces show what is normally seen in very clean 2DESs: strong QHE at

$\nu = 1$ and $2/3$ and, between these fillings, several FQHE states at $\nu = 4/5$, $7/9$, $8/11$, and $5/7$. At the higher n , however, a RIQHE (marked by down arrows) is observed near $1/\nu = 1.20$, as evidenced by an R_{xx} minimum and R_{xy} quantized at h/e^2 . Also evident is a developing RIQHE state between $\nu = 4/5$ and $7/9$, signaled by a dip in R_{xy} (up arrow in Fig. 1(b)). As we detail below, the RIQHE phases near $\nu = 4/5$, as well as similar phases near $\nu = 6/5$ on the low-field flank of $\nu = 1$, show a spectacular evolution with density. An examination of the conditions under which we observe these reentrant phases suggests that they are likely WC states, similar to those observed near $\nu = 1/5$ in high-quality 2DESs, and it is the larger electron layer thickness in our samples that stabilizes them here in the lowest LL near $\nu = 1$.

Our samples were grown by molecular beam epitaxy, and each consist of a wide GaAs quantum well (QW) bounded on each side by undoped $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ spacer layers and Si δ -doped layers. We report here data for

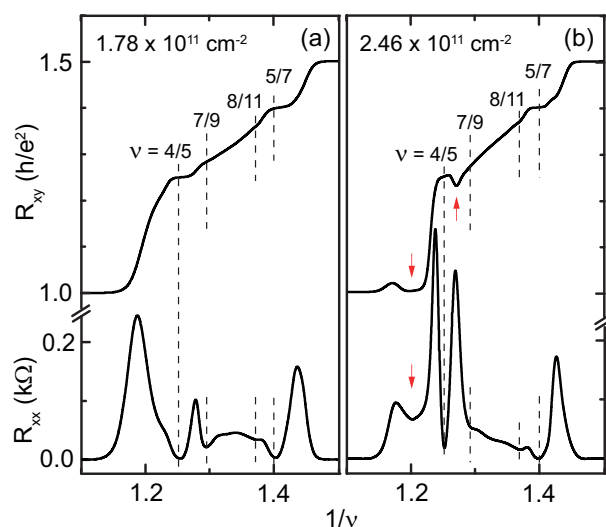


FIG. 1. R_{xx} and R_{xy} vs. $1/\nu$ traces at $T = 30$ mK for a 42-nm-wide GaAs QW at two densities: (a) $n = 1.78$, and (b) $2.46 \times 10^{11} \text{ cm}^{-2}$. In (b) the RIQHE phases observed on two sides of $\nu = 4/5$ are marked by arrows. Note also the two sharp R_{xx} maxima surrounding the $\nu = 4/5$ R_{xx} minimum.

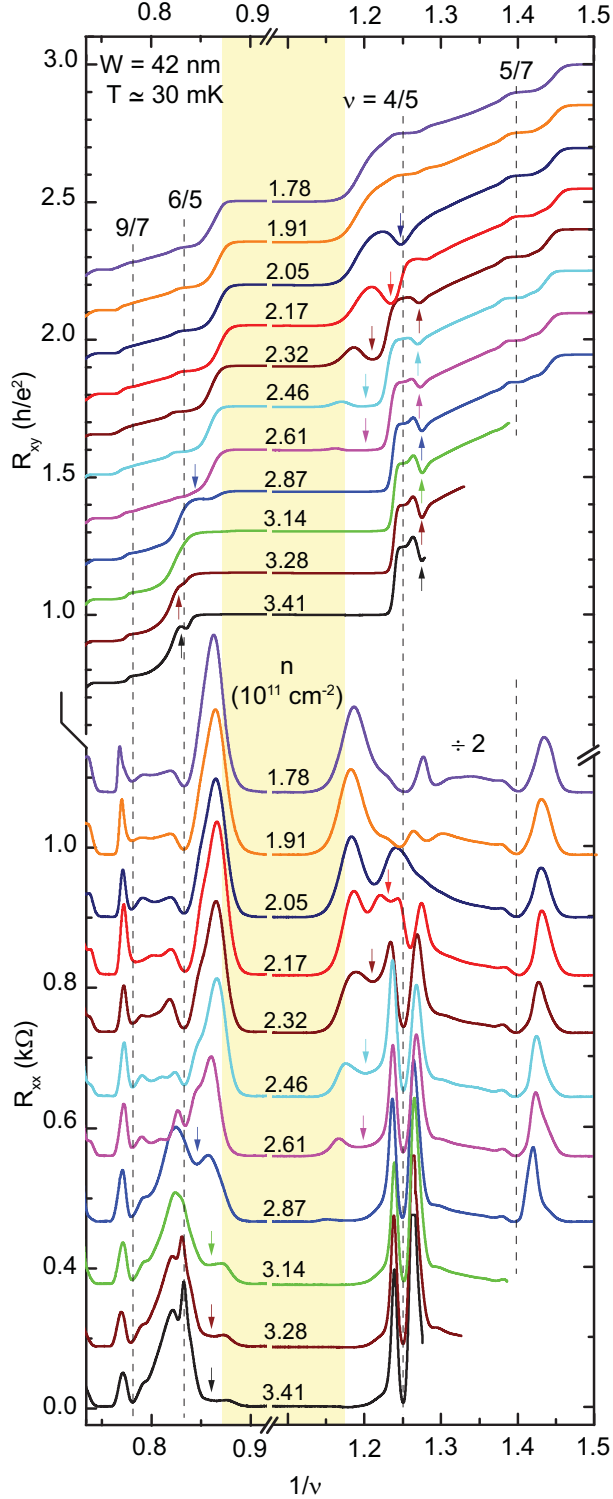


FIG. 2. (color online) Waterfall plots of R_{xx} and R_{xy} vs. $1/\nu$ for the 42-nm-wide QW as n is changed from 1.78 to $3.41 \times 10^{11} \text{ cm}^{-2}$. Traces are shifted vertically for clarity. The down arrows mark the development of RIQHE phases near $1/\nu = 1.20$ as n is raised from 2.05 to $2.61 \times 10^{11} \text{ cm}^{-2}$, and near $1/\nu = 0.86$ as n is further increased. The up arrows in the top panel mark the development of similar, albeit weaker, RIQHE phases near $1/\nu = 1.28$ and 0.83 . The yellow band marks the range $0.85 \leq \nu \leq 1.15$; see text.

three samples, with QW widths $W = 31, 42$ and 44 nm , and as-grown densities of $n \simeq 3.3, 2.5$ and $3.8 \times 10^{11} \text{ cm}^{-2}$, respectively. The low-temperature mobilities of these samples are $\mu \simeq 670, 910$ and $600 \text{ m}^2/\text{Vs}$, respectively. The samples have a van der Pauw geometry and each is fitted with an evaporated Ti/Au front-gate and an In back-gate. We carefully control n and the charge distribution symmetry in the QW by applying voltage biases to these gates [15, 16]. All the data reported here were taken by adjusting the front- and back-gate biases so that the total charge distribution is symmetric. The measurements were carried out in superconducting and resistive magnets with maximum fields of 18 T and 35 T respectively. We used low-frequency ($\simeq 10 \text{ Hz}$) lock-in techniques to measure the transport coefficients.

Figure 2 shows a series of R_{xx} and R_{xy} traces in the range $2/3 < \nu < 4/3$ for the 42-nm-wide QW sample, taken as n is changed from 1.78 to $3.41 \times 10^{11} \text{ cm}^{-2}$. These traces reveal a remarkable evolution for the different reentrant phases of this 2DES. At the lowest n , FQHE states are seen at $\nu = 9/7, 6/5, 4/5$, and $5/7$. When n is increased to $2.05 \times 10^{11} \text{ cm}^{-2}$, the $\nu = 4/5$ FQHE disappears and a minimum in R_{xy} develops near $\nu = 4/5$. As n is further increased, the R_{xy} minimum becomes deeper and moves towards $1/\nu = 1.20$, and an R_{xx} minimum starts to develop at the same filling (see down arrows near $1/\nu = 1.20$ in Fig. 2). Meanwhile, the $\nu = 4/5$ FQHE reappears to the right of these minima. As we keep increasing n , the R_{xy} minimum deepens and becomes quantized at h/e^2 for $n \geq 2.46 \times 10^{11} \text{ cm}^{-2}$, and the R_{xx} minimum gets deeper and vanishes for $n > 2.87 \times 10^{11} \text{ cm}^{-2}$. At the highest n these minima merge into the R_{xy} plateau and the R_{xx} minimum near $\nu = 1$.

Figure 2 traces also show that, with increasing n , another R_{xy} minimum starts to develop on the right side of $\nu = 4/5$, as marked by the up arrows at $1/\nu = 1.28$. This minimum, too, becomes deeper at higher n and, as we will show later, approaches h/e^2 . Also noteworthy are the two sharp R_{xx} maxima on the flanks of $\nu = 4/5$ after the $\nu = 4/5$ FQHE reemerges at high densities.

The evolution observed on the right side of $\nu = 1$ is qualitatively seen on the left side also, but at higher n . The $\nu = 6/5$ FQHE, e.g., disappears at $n = 2.87 \times 10^{11} \text{ cm}^{-2}$ and a dip in R_{xx} develops near $1/\nu = 0.86$ (see down arrows in Fig. 2), concomitant with R_{xy} lifting up and eventually becoming quantized at h/e^2 .

Figure 3 illustrates the T -dependence of R_{xx} and R_{xy} at $n = 2.46 \times 10^{11} \text{ cm}^{-2}$. At the highest T , the R_{xx} and R_{xy} traces near $\nu = 4/5$ look "normal": There is a relatively strong FQHE at $\nu = 4/5$ as signaled by a deep minimum in R_{xx} and an R_{xy} plateau at $5h/4e^2$. Away from $\nu = 4/5$, R_{xy} follows a nearly linear dependence on B . As T is lowered, however, R_{xy} develops a minimum near $1/\nu = 1.20$ which eventually turns to a plateau quantized at h/e^2 at the lowest T . Meanwhile, a strong

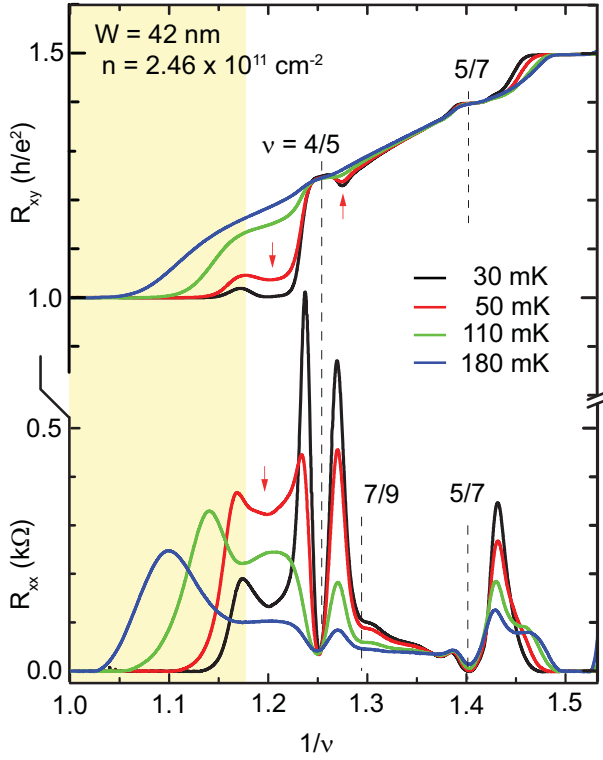


FIG. 3. (color online) Evolution of R_{xx} and R_{xy} with temperature for the 42-nm QW at $n = 2.46 \times 10^{11} \text{ cm}^{-2}$.

minimum develops in R_{xx} at $1/\nu = 1.20$. On the right side of $\nu = 4/5$, another R_{xy} minimum is developing.

Data taken on the 31- and 44-nm-wide QW samples reveal the generality of these phenomena. Figure 4(a) shows data for the 31-nm QW. Similar to the data of Fig. 2, as n is increased, the $\nu = 4/5$ FQHE is quickly destroyed and R_{xy} develops a deep minimum which approaches the $\nu = 1$ plateau at h/e^2 near the highest B that we can achieve in this sample. The resemblance of the traces shown in Fig. 4(a) to the top four R_{xy} and R_{xx} traces in Fig. 2 is clear. Note, however, that in the narrower QW of Fig. 4(a) we need much higher n to reproduce what is seen in the wider QW of Fig. 2.

In Fig. 4(b) we show data for the 44-nm QW at a very high density ($n = 3.83 \times 10^{11} \text{ cm}^{-2}$). Given the larger QW width and higher n of this sample compared to Fig. 2 sample, we expect the RIQHE near $1/\nu = 1.20$ to be fully developed, and the RIQHE on the high-field side of $\nu = 4/5$ whose emergence is hinted at in Fig. 2 R_{xy} traces (see up arrows near $1/\nu = 1.28$ in Fig. 2) to become more pronounced. This is indeed seen in Fig. 4(b): The R_{xy} trace shows a very deep minimum on the high-field side of $\nu = 4/5$ at $1/\nu = 1.28$, nearly reaching the $\nu = 1$ plateau at h/e^2 when the smallest sample current (1 nA) is used to achieve the lowest electron temperature for this sample. Note also the appearance of a small but clearly visible R_{xx} minimum at $1/\nu = 1.28$, consistent with the

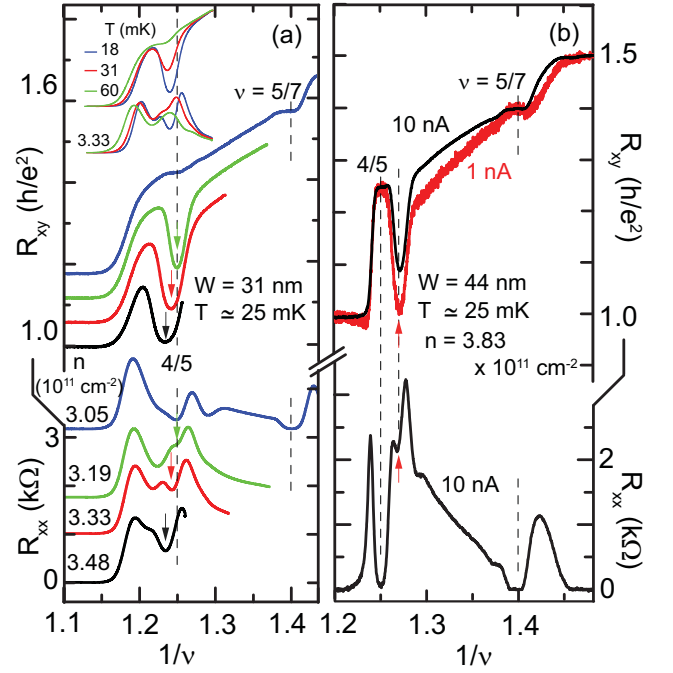


FIG. 4. (color online) (a) Waterfall plots of R_{xx} and R_{xy} vs. $1/\nu$ for the 31-nm QW sample, showing how the RIQHE phase near $1/\nu = 1.20$ starts to develop as n is raised from 3.05 to $3.48 \times 10^{11} \text{ cm}^{-2}$. Data are shifted vertically for clarity. The inset shows the T -dependence of the RIQHE at $n = 3.33 \times 10^{11} \text{ cm}^{-2}$. (b) R_{xx} and R_{xy} traces for the 44-nm QW at $n = 3.83 \times 10^{11} \text{ cm}^{-2}$ displaying a RIQHE phase at $1/\nu = 1.28$.

development of RIQHE at this filling [17].

A natural interpretation of the RIQHE phases that we observe near $\nu = 4/5$ and $6/5$ is that these are pinned WC phases, similar to the insulating phases seen around the $\nu = 1/5$ FQHE and extending to $\nu \ll 1/5$ [6–8]. In the present case, electrons at $\nu = 1 \pm \nu^*$ can be considered as a filled LL, which is inert, plus excess electrons/holes with filling factor ν^* , which could conduct. At sufficiently small values of ν^* and low temperatures, these excess electrons/holes crystallize into a solid phase which is pinned by disorder and does not participate in transport. Thus the magneto-transport coefficients, R_{xx} and R_{xy} , approach those of the $\nu = 1$ IQHE.

In high-quality 2DEs, there have been no prior reports of RIQHE phases near $\nu = 1$ in the lowest LL from low-frequency (essentially dc) magneto-transport measurements [18]. Our results indicate that such RIQHE phases set in only at high densities and in relatively wide QWs. We suggest that it is the large electron layer thickness (spread of the electron wavefunction perpendicular to the 2D plane) in our wide QW samples that induces the WC formation [19]. Supporting this conjecture, theoretical work [20] indeed indicates that in wide QWs, thanks to the softening of the Coulomb interaction at short distances, a WC phase is favored over the FQHE liquid state if the QW width becomes several times larger

than the magnetic length (l_B). In our samples, W/l_B is large and ranges from $\simeq 4.6$ to $\simeq 6.0$ at the densities above which we start to observe the RIQHE near $\nu = 4/5$, qualitatively consistent with the theoretical results.

In a relevant study, high-frequency (microwave) resonances were observed very close to $\nu = 1$ ($\nu^* < 0.15$) in high-quality 2DESs and were interpreted as signatures of a pinned WC [21]. We have highlighted this filling range with a yellow band in Figs. 2 and 3. This is the range where we see a deep R_{xx} minimum and a very well quantized R_{xy} (at h/e^2), signaling a strong $\nu = 1$ QHE. In our samples, however, we observe RIQHE phases at relatively large values of ν^* , extending to $\nu^* > 1/5$. In particular, $1/\nu \simeq 1.28$ where we see the RIQHE on the right side of $\nu = 4/5$ corresponds to $\nu^* \simeq 0.22$. This is clearly outside the ν^* range where Chen *et al.* observed microwave resonances, indicating that the RIQHE phases we are reporting here are distinct from the phase documented in Ref. [21]. Also the RIQHE we observe at $1/\nu = 1.20$ ($\nu^* \simeq 0.17$) is separated from the deep QHE region very near $\nu = 1$ by maxima in R_{xx} and R_{xy} (see, e.g., the right-hand-side edge of the yellow band in Figs. 2 and 3). This observation provides additional evidence that two distinct insulating phases exist. If so, then these resistance maxima signal additional scattering at the domain walls separating these phases.

It is worth noting that microwave experiments at very small ν have revealed two distinct resonances [22]. One resonance ("A") was seen in the insulating phases reentrant around $\nu = 1/5$, and another ("B") was dominant at very small fillings ($\nu < 0.15$). It was suggested that these resonances signal the existence of two different types of correlated WCs, stabilized by the crystallization of composite Fermions with different number of flux quanta attached to them. Such an interpretation is corroborated by theoretical calculations [23, 24]. It is tempting to associate the RIQHE phases we observe reentrant around $\nu = 4/5$ ($\nu^* = 1/5$) with the type "A" WC and the resonance seen very near $\nu = 1$ ($\nu^* < 0.15$) in Ref. [21] with the type "B" WC.

A very intriguing aspect of our data is the disappearance followed by a rapid reemergence of the $\nu = 4/5$ ($\nu^* = 1/5$) FQHE when the RIQHE near $\nu = 4/5$ starts to be seen [25]. We do not have a clear explanation for this observation. We speculate that it might signal the existence of multiple types of WC phases that have ground-state energies very close to the ground-state energy of the FQHE liquid phase. Theoretical calculations indeed indicate that such WC phases, which are based on composite Fermion FQHE liquid wavefunctions, do exist and might well describe the insulating phases observed near $\nu = 1/5$ [23, 24]. The disappearance and reappearance of the $\nu = 4/5$ FQHE we observe may stem from a close competition between the FQHE and such WC states. Consistent with this scenario is the following observation in Fig. 4(a). When the $\nu = 4/5$ FQHE dis-

appears, R_{xy} at $\nu = 4/5$ immediately starts to dip down towards h/e^2 , suggesting a transition to a RIQHE phase. This is in sharp contrast to R_{xy} maintaining its value of $5h/4e^2$ on the classical Hall line, if the $\nu = 4/5$ FQHE state made a transition to a compressible liquid phase.

In conclusion, we observe RIQHE phases near $\nu = 4/5$ and $6/5$ in the lowest LL in very clean 2DESs confined to relatively wide GaAs QWs. In a given QW, the RIQHE is absent at low densities and develops above a certain density which is higher for narrower QWs. Our observations are consistent with the crystallization of excess electrons/holes in the unfilled lowest LL into a WC.

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